Long-Period Ground-Motion Simulations of the M_w 7.2 El Mayor-Cucapah Mainshock: Evaluation of Finite-Fault Rupture Characterization and 3D Seismic Velocity Models

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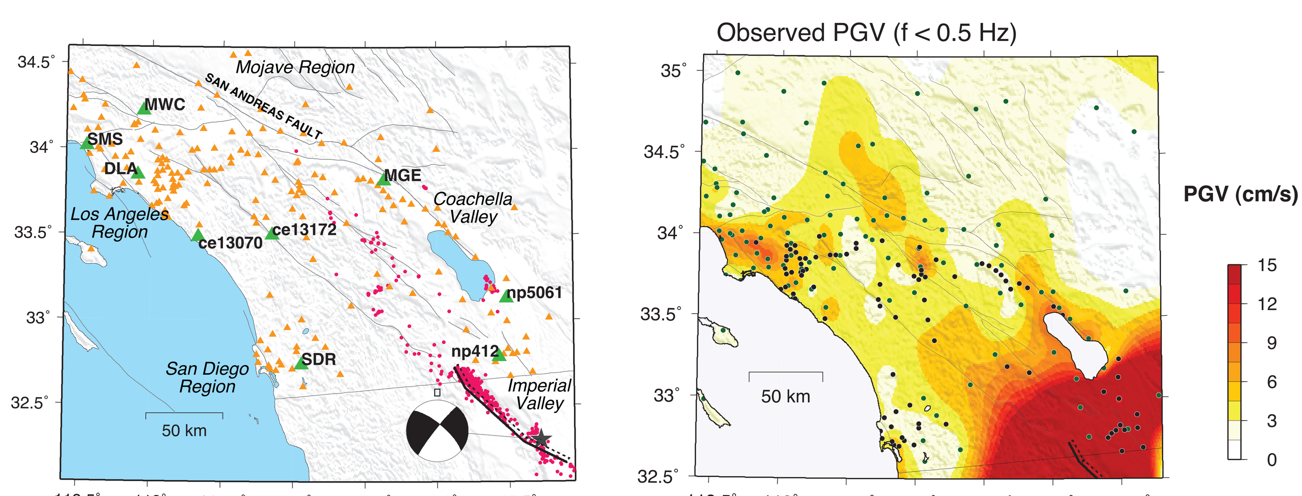
Summary

Using a suite of five hypothetical finite-fault rupture models, we test the ability of long-period (T > 2.0 s) ground-motion simulations of scenario earthquakes to produce waveforms throughout southern California consistent with those recorded during the 4 April 2010 Mw 7.2 El Mayor-Cucapah earthquake. The hypothetical ruptures are generated using the methodology proposed by Graves and Pitarka (2010) and require, as inputs, only a general description of the fault location and geometry, event magnitude and hypocenter, as would be done for a scenario event. For each rupture model, two Southern California Earthquake Center (SCEC) 3D community seismic velocity models (CVM-4m and CVM-H62) are used, resulting in a total of 10 ground-motion simulations, which we compare with ground motions recorded at over 200 sites throughout southern California. While the details of the motions vary across the simulations, the median levels match the observed peak ground velocities reasonably well with the standard deviation of the residuals generally within 50% of the median. Considering the entire model region, simulations with the CVM-4m model yield somewhat lower variance than those with the CVM-H62 model. However, for the non-basin regions, simulations with the CVM-H62 model perform significantly better than those of CVM-4m, which we attribute to the inclusion of the Tape et al. (2009) tomographic updates within the background crustal velocity structure of CVM-H62. Both models tend to over-predict motions in the San Diego region and under-predict motions in the Imperial basin and the Mojave desert. Within the greater Los Angeles basin, the CVM-4m model generally matches the level of observed motions whereas the CVM-H62 model over-predicts the motions in the southernmost portion of the basin. Animations of the simulated wave fields demonstrate this over-prediction is created by the sharp impedance contrast along the southern margin of the Los Angeles basin in the CVM-H62 model. For both seismic velocity models, the variance in the peak velocity residuals is lowest for a rupture that has significant shallow slip (less than 5 km depth), whereas the variance in the residuals is greatest for ruptures with large asperities below 10 km depth. Overall, these results are encouraging and provide confidence in the predictive capabilities of the simulation methodology, while also suggesting regions where the seismic velocity models may need improvement.

Ground-Motion Observations



Mainshock mechanism:
http://earthquake.usgs.gov/earthquakes/eqinthenews/2010/ci14607652/ci14607652_cmt.php

The El Mayor-Cucapah earthquake occurred at 22:40:42 UTC (3:40 pm PDT) on 4 April 2010 in northern Baja California with a moment magnitude of 7.2 and a normal-oblique focal mechanism. Top left figure shows the epicenters of the mainshock and first 24 hours of aftershocks (Hauksson et al., 2010). The locations of the mainshock and aftershocks, as well as the mainshock focal mechanism initially suggested the rupture occurred on the Laguna Salada fault. In the hours immediately following the mainshock, we constructed a three segment fault model that roughly follows the Laguna Salada fault trace taken from the SCEC Community Fault Model. Our fault model does not exactly follow the Laguna Salada geometry, and in particular dips to the east, in order to be consistent with the mainshock focal mechanism. Subsequent field analysis suggests that actual rupture occurred on the Borrego and Pescadores faults lying just east of the Laguna Salada (Fletcher et al., 2010). However, for our long-period modeling this distinction is not significant.

Ground-motion waveforms of the El Mayor-Cucapah event were recorded at over 200 strong-motion sites throughout southern California and northern Baja California. Processed records from many strong-motion sites operated by the California Geological Survey (CGS) and the Southern California Seismic Network (SCSN, operated by Caltech and the USGS) became available soon after the event, and were distributed through www.strongmotioncenter.org and www.data.scec.org. The locations of the recording sites for which data were obtained as of 08 April, 2010 are shown in the top left figure. Data were further processed by integrating to ground velocity and low-pass filtering with a zero-phase, 4th order Butterworth operator having a corner at 0.5 Hz. For each recording site, the maximum peak ground velocity (PGV) was measured from the low-pass filtered motions.

The top right figure plots the observed PGV in map view for the southern California region. The strongest motions are in the near fault region and extend eastward into the Imperial Valley. While there is a general decrease in amplitude with increasing distance from the fault, the spatial distribution of PGV exhibits noticeable complexity and variability. Areas of relatively strong motions occur in the Coachella Valley, the San Bernardino and Mojave regions, and most significantly in the Los Angeles basin region. Areas of relatively weak motions occur west of the Coachella Valley and in the San Diego region. We interpret these features to be related to wave propagation effects within the heterogeneous crustal structure of the southern California region.

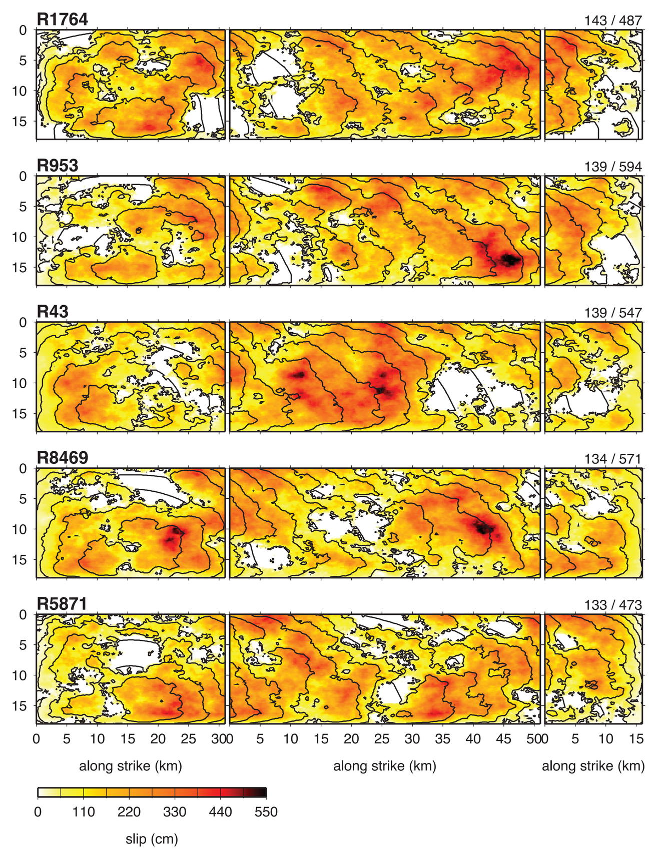
Simulation Methodology

The simulation is carried out using a parallelized 3D viscoelastic, finite-difference algorithm and incorporates both complex source rupture, as well as wave propagation effects within arbitrarily heterogeneous 3D geologic structure. Anelastic attenuation is incorporated using the coarse-grain approach (Day and Bradley, 2001) with the quality factors given by the relations Qs = 50Vs (for Vs in km/s) and Qp = 2Qs. In the near surface layers, we limit the minimum shear velocity to 0.5 km/s, which dictates a grid size of 0.2 km for accurate wave propagation results in the bandwidth T > 2 s with 4th order spatial finite-difference operators.

Scenario Rupture Models

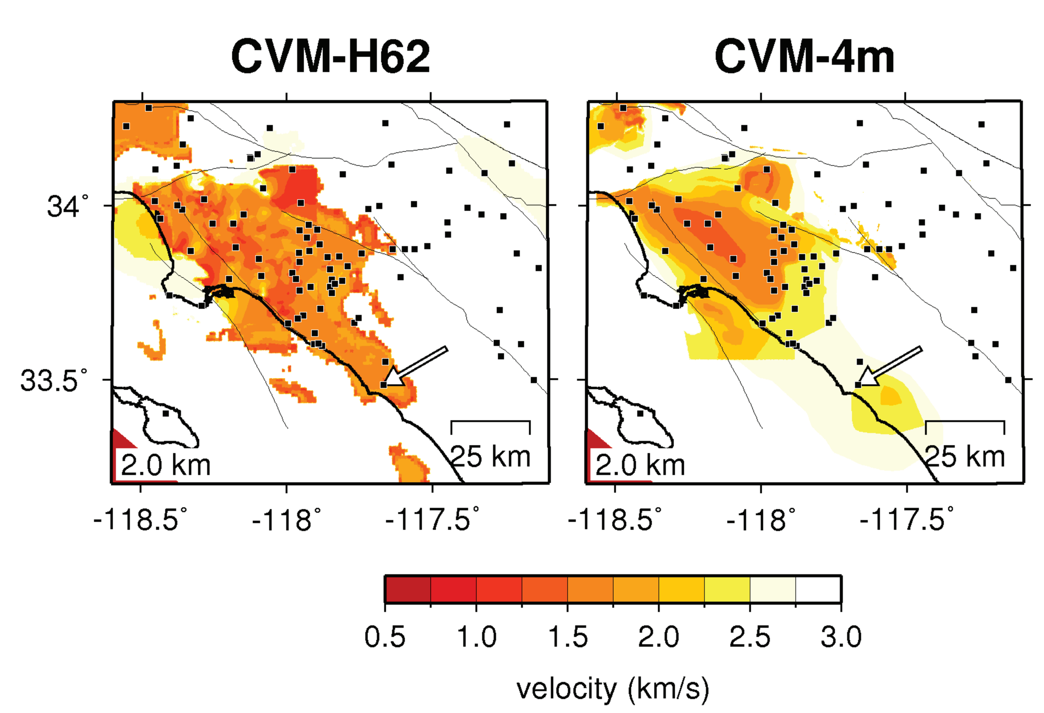
We construct a suite of five hypothetical kinematic rupture models using the procedure of Graves and Pitarka (2010). In constructing these models, we fix the magnitude and hypocenter as these parameters are known to have a significant influence on the radiated ground motions. The ruptures are generated such that the amplitude spectrum of slip follows a wavenumber squared falloff with random phasing. The mean slip is scaled to achieve the mainshock moment (7.8×10^{26} dyne-cm on average) with the standard deviation of slip set at 85% of the mean slip.

The background rupture propagation speed is set at 80% of the local shear wave velocity with local perturbations dependent on fault segmentation and local slip. The slip rate function is from Liu et al. (2006) with a rise time that scales with square root of local slip (Aagaard et al., 2008) and lengthens by a factor of two in the upper 5 km of rupture. The average value of rise time is 1.47 sec, which is constrained to match the Somerville et al. (1999) scaling relation. Finally, the slip direction (rake) is allowed to vary across the fault with a standard deviation of 15 degrees about a prescribed mean value of 200°. Figure at right plots the slip distribution and rupture propagation contours for these five rupture scenarios.



Seismic Velocity Models

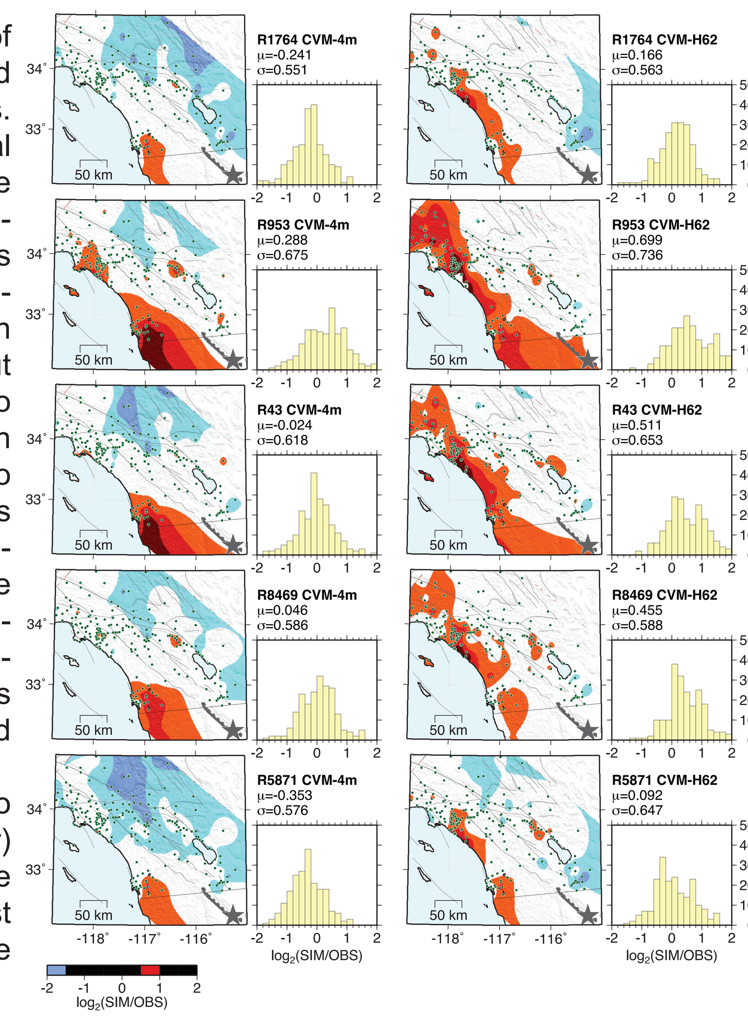
For our simulations, we consider two alternative 3D seismic velocity models. The basis for the first model (CVM-4m) is the SCEC CVM-4.0 (Magistrale et al., 2000; Kohler et al., 2003), to which we then apply modifications based on the modeling analysis of Graves and Pitarka (2010). These modifications consist of replacing the upper 2 km of the background (i.e., non-basin) structure with the Boore-Joyner generic rock profile (Boore and Joyner, 1997) and replacing the Vp/Vs relation for sediments of the Imperial Valley with the "mudline" relation of Brocher (2005). Graves and Pitarka (2010) found that these modifications provided more realistic representations of the velocity structure in these regions of the model and provided improved fits to observed earthquake ground motions. The second model, CVM-H62, is version 6.2 of the SCEC CVM-H (Shaw and Suess, 2003). This model includes the tomographic updates of Tape et al. (2009) within the background crustal structure, as well as the Boore-Joyner generic rock profiles in the shallow (upper 300 m), non-basin portions of the model.



Horizontal slices showing shear wave velocity in the Los Angeles basin region at a depth of 2 km for models CVM-H62 (left) and CVM-4m (right). Locations of recording sites are indicated by the dark circles. The large arrow indicates the location of station ce13070, which is discussed in the panels to the right.

Simulation Results

The adjacent figure plots the ratio of the synthetic PGV to the observed value for each of the 10 simulations. From these comparisons, several consistent trends are seen. The median residual PGV across all simulations using the CVM-4m model is generally centered about zero, ranging from 21% under-prediction (rupture scenario R5871) to about 23% over-prediction (rupture scenario R953); and with a standard deviation that ranges between roughly 45 to 50% of the median. In addition, this model does reasonably well in matching the observed PGV levels in the western Imperial Valley and Los Angeles basin regions, with the simulated PGV at many individual sites within 20 to 30% of the observed values. This model tends to over-predict the motions in the San Diego region (up to a factor of 2 or greater) and under-predict the motions in the eastern Imperial Valley and northeast of the San Andreas fault in the Mojave desert (up to a factor of 2).



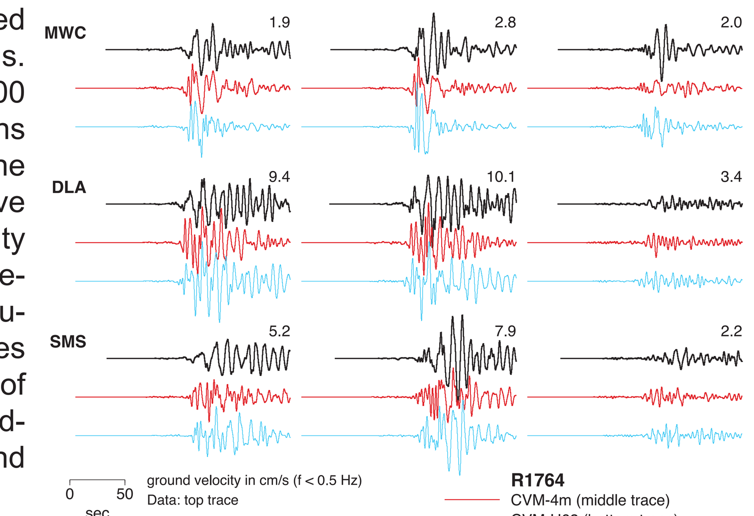
The median residuals for simulations using the CVM-H62 model range from near zero (R5871) to 63% over-prediction (R953), and the standard deviation ranges between roughly 55 to 75% of the median. This standard deviation is larger than that for the CVM-4m simulations. The CVM-H62 significantly over-predicts the peak amplitudes in the Los Angeles basin region, particularly at the southern margin of the basin where the simulated values are generally 2 to 3 times larger than the observed values. The large over-prediction in this region leads to the general positive bias in the PGV residuals for the CVM-H62 simulations and larger standard deviation relative to the CVM-4m simulations. Nonetheless, this model does reasonably well in matching the observed PGV in the central portion of the model region. Similar to the CVM-4m model, the CVM-H62 model tends to over-predict the motions in San Diego (by roughly 50%) and under predict the motions in the eastern Imperial Valley and east and north of the San Andreas fault (by roughly 50%), although the range of variance is not as strong in these regions as that seen for the CVM-4m results.

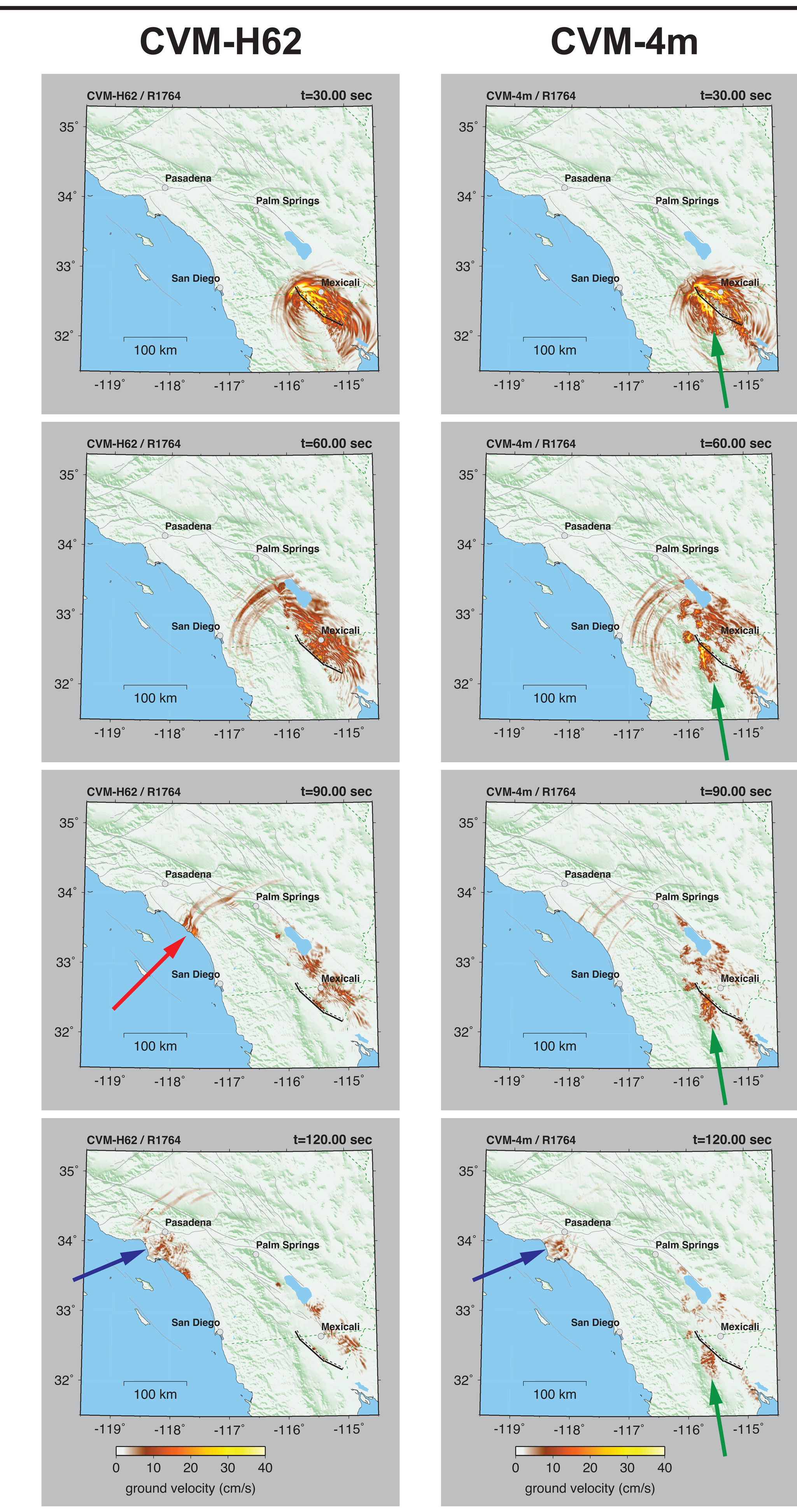
Averaged over the two velocity models, rupture R1764 produces the median residual that is closest to zero (about 5% under-prediction), rupture R953 has the greatest positive median residual (over-prediction of about 41%), and rupture R5871 has the greatest negative median residual (under-prediction of about 16%). For both velocity structures, rupture R1764 produces the lowest standard deviation (about 47% of the median) and rupture R953 produces the highest standard deviation (about 60 to 65% of the median). This suggests that features of rupture R1764 such as the large shallow slip patch near the junction of the second and third segments are more consistent with the observed ground motions, whereas features of rupture R953 such as the generally deeper slip and deep asperity with large slip on the second segment are less consistent with the recorded motions.

Waveform Comparisons

The adjacent figure compares observed and simulated waveforms for three sites in the central and western portion of the Los Angeles basin region. At these sites, the peak amplitudes are matched to within about 20 to 30% by the simulations for both seismic velocity models. In addition, both models provide a good fit to the shape and duration of the observed waveforms, particularly at station MWC, which is located north of the basin in the San Gabriel Mountains. Station DLA is situated over the deepest portion of the basin (about 9 to 10 km of sediments), and the motions at this site are characterized by a series of large amplitude arrivals lasting for at least 40 to 50 seconds, with peak amplitudes over 10 cm/s (about 3 to 4 times larger than the motions at MWC). Station SMS is located along the western margin of the basin where the sediment thickness is about 3 to 4 km. The motions at this site are about 2 to 3 times larger than the motions at the non-basin site MWC, and they exhibit a series of large amplitude arrivals lasting at least 50 seconds.

All of these features are reproduced reasonably well by the simulations. Since these sites are located about 200 km from the fault rupture, the motions are less insensitive to the details of the rupture process and are more sensitive to the character of the seismic velocity structure. The generally good agreement between the observed and simulated waveforms at these sites provides a degree of confidence in the ability of the seismic velocity models to adequately capture long-period path and basin response effects.





Wave Field Animations

All of the simulated scenarios exhibit strong northwestward directivity and significant 3D wave propagation effects. The above panels show sanpshots of simulated ground velocity for rupture scenario R1764 in both seismic velocity models (CVM-H62 on left, CVM-4m on right), which highlight the main features common to all the scenarios. Since the rupture occurred along the western boundary of the Imperial Valley, significant wave energy is channeled into the deep sediments of this basin structure. This leads to strong amplification of motions and extended durations of strong ground shaking throughout the Imperial and Coachella Valleys. At later times, a strong basin response is also evident in the Los Angeles basin located roughly 200 km northwest of the rupture (blue arrow at t=120 s). The CVM-4m includes the Laguna Salada basin just to the west of the rupture (green arrow on right panels), and predicts strong amplification and extended durations in this area that are not present in CVM-H62. The animations also clearly demonstrate the CVM-H62 structure produces a much stronger channeling and trapping of wave energy in the southern Los Angeles basin compared to the CVM-4m structure (red arrow at t=90 s), leading to amplified motions throughout the southern and eastern portions of the Los Angeles basin in the CVM-H62 model.

Acknowledgements

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